NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM

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FLOW INVESTIGATION WITH THE AID OF THE ULTRAMICROSCOPE

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SUMMARY

On the basis of photographic pictures the laminar flow at a pipe inlet was measured and compared with other measurements and computational results. The test setup is described in detail, and a series of the pictures obtained for turbulent flow is given.

INTRODUCTION

The ultramicroscope has been adopted by Fage and Townend (reference 1) as an aid in flow investigation. The method has further been developed and refined so that flow photographs are obtained from which measurable results can be derived.

OBSERVATION PROCEDURE

Flows can, in general, be rendered visible only by introducing foreign bodies in the fluid, the experimental difficulties varying with the nature of these bodies and that of the flow. Very rapid or very slow processes are difficult to follow, but the greatest difficulties are encountered in investigating the fine structure of the flow processes. In this connection Fage and Townend present a simple and widely applicable as well as reliable method: namely, that of rendering visible the very fine particles contained in the water by dark field illumination. Such particles, even after the most careful purification of the water, always remain in sufficiently large number. They are not visible in ordinary light just as the dust particles contained in the air which only become visible in a thin ray of sunlight admitted into a dark room. Owing to the smallness of these particles it may be assumed that

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[1]"Stromungsuntersuchung mit dem Ultramikroskop." Forschung auf dem Gebiete des Ingenieurwesens, vol. 8, pt. 1, Jan.-Feb. 1937, pp. 42-47.

they carry out the same motion as that of the surrounding fluid.[1]

DESCRIPTION OF THE TEST SETUP

Figure 1 shows the construction of the test setup. From the arc lamp a the light passes through the condenser b, the cylindrical lens c and the adjustable slit d into the illumination objective e which at the point of the pipe to be investigated f produces, as an image of the slit, a thin beam of light of accurately measurable thickness. At right angles to it the image is observed by the microscope g. Instead of the usual tube the microscope has a U-shaped base so that the ray path can be modified by a rotating lens disk h. In this way the motion in the direction of the pipe axis can with a suitable rotational speed be balanced out so that the particles are seen at rest in the ocular and the deviations from the axial velocity, which are of importance for turbulence investigations, can be studied. In this manner, too, the velocity itself can be determined from the rotational speed without the need for introducing a measuring apparatus which disturbs the flow. Fage and Townend use a rotating objective instead of the lens disk.

The magnifications lie at about 20 to 50 and in exceptional cases 100 to 150 times are possible. With the water at rest there is obtained the impression of observing a starry sky. Small particles carry out the Brownian movement, thus leading to the supposition of orders of magnitude below 1 μ. With the fluid in motion there are seen the pictures of figures 2a to 2h.

MEASURING SETUP FOR ROUND PIPE

Since the directions of illimination and observation are at right angles to each other, Fage and Townend use chiefly a square metal pipe in which windows are mounted. In these tests it was not possible, however, to obtain a transition from the metal to the glass wall as free from disturbance as was desirable; also, the smoothness of the drawn brass pipe differed appreciably from that of the glass plate. Hence, in order to avoid every disturbance the round glass pipe was used for the further tests.

The cylindrical surfaces did not directly afford an observation because, aside from the astigmatic distortion, only about 75 percent of the

[1]The idea of the ultramicroscope is in itself not connected either with the size of the particles or a high magnification, but is based essentially on the fact that particles invisible under ordinary illumination become visible under illumination against a dark background. In this manner particles up to 0.005 μ can be observed, which lie below the resolving limit of the microscope optical system (0.3 to 0.1 μ) and hence the name ultramicroscope.

pipe cross section is visible. To balance the error, the simple small tank i filled with water (fig. 1) was found most suitable. A specially prepared calibration scale automatically adjustable in the center of the pipe (fig. 3) was used to balance the residual error due to the glass wall on evaluating the measurements so that the position of an observed point in the pipe could be reliably determined. Figure 4 shows a picture of the scale - the pipe and tank are filled with water - and indicates the usefulness of a simple tank within a wide range. For judging the sharpness of the picture, compare also figures 6 and 7. Only for observations in the immediate neighborhood of the wall was a modification necessary. Thus, the astigmatic distortion at the tips of the scale could be eliminated by using a fluid in the tank of higher index of refraction than water, for example, by the addition of glycerine.

Other difficulties arise in investigating the layer near the wall in the plane parallel to the wall. In this case the arrangement shown in figure 5 proved useful. By puttying two glass plates and filling out the interspaces with cedarwood oil, which has the same index of refraction as glass, the ray path indicated was made possible.

QUALITATIVE OBSERVATIONS

The previously described apparatus was for the purpose of verifying the observations reported by Fage and Townend on the flow process in the immediate neighborhood of the wall for the condition of turbulence: namely, that the particles there do not carry out a rectilinear motion in the direction of the pipe axis as may at first be supposed. According to the previously mentioned difficulties in the accurate puttying of the windows, a disturbance arising from this cause might give rise to the transverse motion. Observations in both the square and circular pipes confirm the English results. They were not, however, further evaluated, since the inaccuracies and roughnesses of the glass surface for commercial tubes rendered impossible a truly fine investigation. Figures 7 and 8 show how the glass wall becomes visible.

PHOTOGRAPHIC PICTURES

Attempts had been made by English investigators to photograph the pictures visible in the microscope on photographic plates, but the small light intensity was considered to be insufficient. The same answer was given also by experienced microphotographers, and in fact attempts made with the usual microcameras were a complete failure. Since the picture appeared to be very bright, however, the attempts were continued in two directions; (1) raising the light intensity of the arc lamp by increasing the current from 6 to 60 amperes, a method which did not lead to the desired object, (2) dispensing with the magnification of the pictures before photographing. With ordinary tap water there are thus obtained pictures of a few particularly bright particles. In order to obtain pictures from which data may be evaluated, small quantities of very fine particles were further added to the water for the purpose of increasing the number of illuminated particles. Very fine aluminum powder appeared most suitable; whereas collodial solutions, such as used for making visible the Brownian motion, gave only a mistlike increase in the brightness of the light beam.

Figure 6 shows a light beam for an addition of 0.1g aluminum powder per 100 liters of water as used for the measurements, while figure 7 for comparison shows the results for tap water that remained for 2 days exposed to the air. The aluminum particles have the advantage over the natural impurities in that the very small particles which do not give any sharp images in the motion, but only a general obscurity, drop out. Furthermore, the light intensity of the aluminum particles is considerably higher than that of the equal size natural particles.

The additive does not produce difficulties in the case of turbulent motion since the particles can be stirred freely and therefore do not settle. In the case of laminar processes which, on account of the smaller velocity, give brighter pictures, stirring is not possible because of the required nondisturbance of the motion. It is advisable to strew the enlarged particles on the water with a sieve in order to prevent conglomerations. In this way the bright thicker particles are prevented from settling first.

Determinations of the size of the particles from the sinking velocity and their number per unit weight gave consistently an order of magnitude below 10 μ. An estimate of the resistance from their very small sinking velocity in water at rest gave further the result that less than 0.005 second is required to reach a state for which there is the admissible deviation of 1 percent between the particle velocity and that of the surrounding water for arbitrary constant acceleration. There is thus practically obtained in the plate photograph of the path of a particle a very faithful image of the fluid motion.

VELOCITY MEASUREMENT

The pictures given in figure 2 which are obtained on the rotating lens disk do not, even with the above-described means, permit being photographed, because such a small turbulence field can be obtained clearly only with at least 50 magnification. It is further necessary, in order to obtain a photograph, that the ray path of the arc lamp be interrupted periodically by a toothed disk whereby strokes of definite length are obtained which permit the direct measurement of the velocity. A motor was used rotating at $n = 2500$ rpm and a disk with two sectors (eight sectors for turbulent processes), the uniformity of the rotational motion being controlled stroboscopically with the aid of a glow lamp controlled by a tuning fork. In this way an accuracy of 0.1 percent in determining the time was attained.

In the course of the measurements these pictures were produced by two different methods: (1) pictures corresponding to the microscopic investigation, characterized by as high a sharpness of image as attainable and accurately determined arbitrarily thin light beam, (2) pictures over the entire cross section except for the 5-percent outermost part at the edge. An objective of long focus was used for illimination; the width of the slit was up to about 4 percent of the diameter[1]. The second method is more convenient in the test and in general also more productive of results.

APPLICATION OF THE METHOD TO THE LAMINAR FLOW AT A PIPE INLET

It was of particular interest to measure the gradual transition from the almost rectangular velocity distribution at the inlet up to the Poiseuille parabola, since the only available data were those of Nikuradse, (reference 2) and one of the authors of the present paper has also given a method for the approximate computation of the profiles in a circular pipe (reference 3).

There were first combined the velocity profiles of a laminar flow near the inlet from pictures which extended only over a part of the cross section (fig. 8). It was found that the points of a partial photograph generally agreed well with one another, but in spite of equal test conditions could not always be combined to give a unique velocity distribution. Even for small Reynolds numbers ($Re = \bar{u}r/v$ between 300 and 400), it was also found further that on a plate a small velocity was recorded between two larger velocities. The deviations could not lie within the range of observation error and there remained only the possibility that fluctuations occurred in the velocity distributions which are so slow that the laminar character of the flow: namely, the parallelness of the paths, is only slightly disturbed.

[1]This may at first glance appear as inadmissibly large. Since, however, the thickness of the layer only enters to the second order as an inaccuracy in the determination of the point of a field with axial symmetry there is obtained in the neighborhood of the wall, where the velocity gradient is steep, an error of only 0.16 percent.

The above-mentioned photographs over the entire cross section were therefore taken (fig. 9). These could be arranged into three groups: (1) sufficiently regular formation of the velocity profile, (2) formation of the velocity profile on one side, (3) strong scatter about a mean position. Those under (1) and (3) and the previous partial photographs may evidently be reduced to the phenomenon given under (2). The velocity profile oscillates about a mean position. The profiles show the characteristic property that the mean instantaneous value of the velocity $\bar{u}$ over the cross section does not vary in spite of the fluctuation. This constancy was recognizable at the outlet diaphragm, used as a throttle, with connected free stream, which is an extremely sensitive indicator for the finest fluctuations. A light blowing on the water surface, for example, is sufficient to change its glassy clear appearance. A graphical evaluation of the curves of figure 9 also gives the same flow quantity with the restriction that with unsymmetry through the slot the velocity profile cannot be considered as entirely two-dimensional, the difference amounting to 0.3 percent.

In observation by eye some of these fluctuations are subjected to an averaging process but the characteristics of the fluctuations essentially remain, as is seen in figure 10, in which the individual measurements of two profiles are plotted, the two halves being placed next to each other. Near the center of the radius at the left is a point about which the profile seems to oscillate. The right profile has a stable core with constant velocity, but the transition to the velocity zero at the wall shows strong scatter and indicates great lack of stability. The core appears to oscillate radially in the pipe as may be concluded from the observations of Naumann with colored streamers. (See reference 4).

The quasi-stationary state is obtained by the averaging of relatively few values with sufficient accuracy, figure 11; figure 12 shows the profiles. For comparison, the measurements of Nikuradse are also plotted on the figure. The commercial glass pipe used for these measurements permits, however, the possibility of systematic errors, since its cross-sectional area fluctuated by about 4 percent. The separate points were obtained by varying the measuring station x and the mean flow velocity $\bar{u}$.

In order to find to what extent the observed fluctuations depend on the inaccuracies of the pipe and on the mounting base, which was not free from vibrations, it was proposed to build a new test setup on a fixed base and using a Jena KP pipe.

TURBULENCE PHOTOGRAPHS

For the further testing with the object of photographing turbulent processes there was used the above-mentioned precision pipe of 20.5-millimeter diameter. Unfortunately, the accuracy of the diameter (0.2

percent) was gained at the expense of optical disadvantages, since the inner surface, by the drawing process, is rendered insufficiently smooth - the sharpness of the regions near the rim suffering in particular.

For turbulence investigations, for the purpose of statistical evaluation, many photographs are required. For this reason, the microscope objective with the plate photography used thus far were discarded. By using a Leica (Summar 1:2) and additional apparatus with mat disks for pictures in the scale 1:1 the test setup could be made more sensitive and flexible. Figures 13 and 14 show the pictures taken, but do not give the details of the negative. Of interest in many pictures is their almost laminar appearance without any appreciable change in the type of flow and the simultaneously observed outflow parabola of the free jet. It is therefore here a question of a partial turbulence of a state and not of the occurrence of the so-called intermittent turbulence.

By varying the cut-off time, which for sufficient addition of particles can be made sufficiently small - the interruption of the illumination for measuring the velocity must naturally be made considerably shorter - the frequencies may be estimated and the development of velocity fields determined.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.

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2. Prandtl-Tietjens: Hydro- und Aeromechanik. Vol. 2, Julius Springer (Berlin), 1931, p. 27.
3. Vogelpohl, G.: Z. f. a. M. M., vol. 13 (1933) p. 446.
4. Naumann, A.: Forschung auf dem gebiete des Ingenieurwesens., vol. 2 (1931), p. 85.

a, arc lamp
b, condenser
c, cylinder lens
d, slit
e, illuminating objective
f, pipe
g, microscope
h, rotating lens disk
i, tank

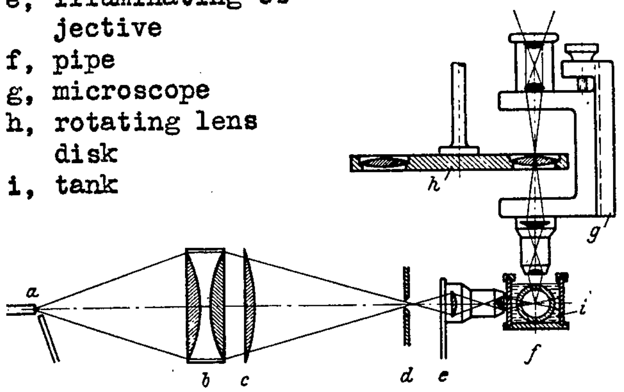
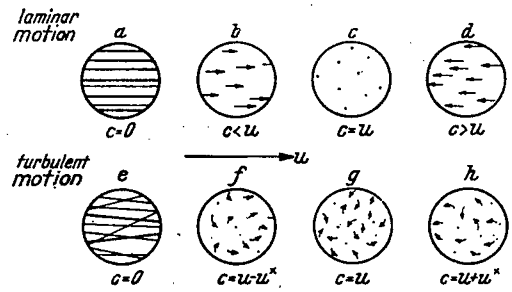


Figure 1.- Test set-up for the observation of flow processes in a pipe with the aid of the ultramicroscope.



c, equalizing velocity of the lens disk
u, particle velocity (time-averaged value at a definite point)
u^x, disturbance velocity of the turbulence motion

Figure 2.- Observed flow pictures with rotating lens disk.

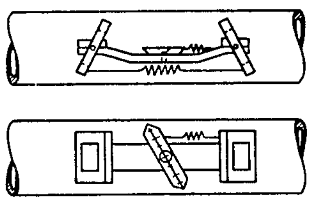


Figure 3.- Scale for calibrating the optical system.

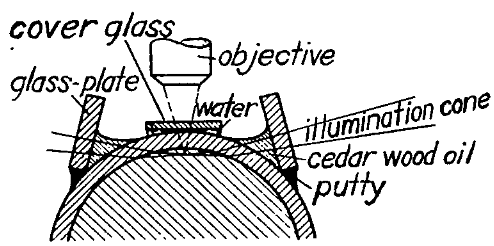


Figure 5.- Arrangement for investigating the flow in the neighborhood of the wall.

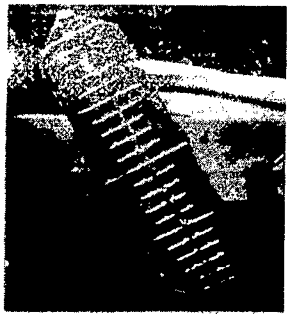


Figure 4.- Calibrating scale in pipe. The water-filled tank annuls the distortion of the picture except for small errors at the edge.

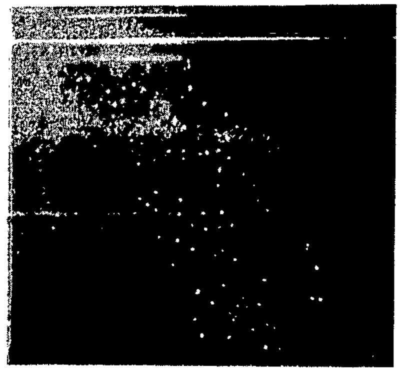


Figure 6.- Aluminum powder in water under dark field illumination. Exposure time 1/20 seconds.

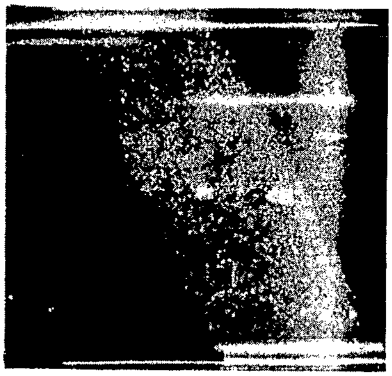


Figure 7.- Light beam through water remaining stagnant for two days. Exposure time 1/4 seconds.

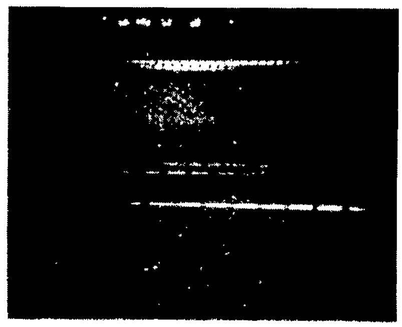


Figure 8.- Partial photograph of laminar flow in the neighborhood of the wall.

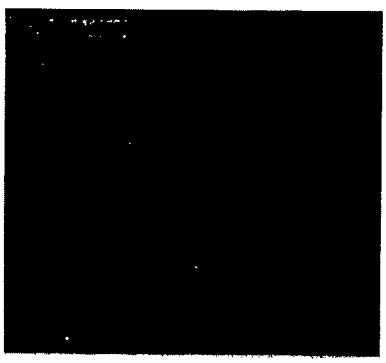


Figure 13.- Turbulent flow Re = 2190, sharp edged inlet. Added particles 10^{-6} the volume of water, illumination 50 A, exposure time 1/4 seconds. Space between strokes corresponds to a time of 1/200 seconds.

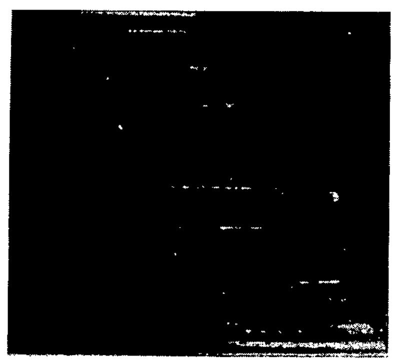


Figure 14.- Turbulent flow Re = 2190, sharp edged inlet. Added particles 10^{-6} the volume of water, illumination 50 A, exposure time 1/8 seconds. Space between strokes corresponds to a time of 1/200 seconds.

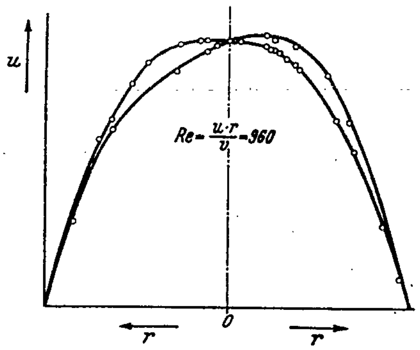


Figure 9.- Scatter of the velocity profile at the inlet. Laminar velocity profiles photographically obtained under equal test conditions.

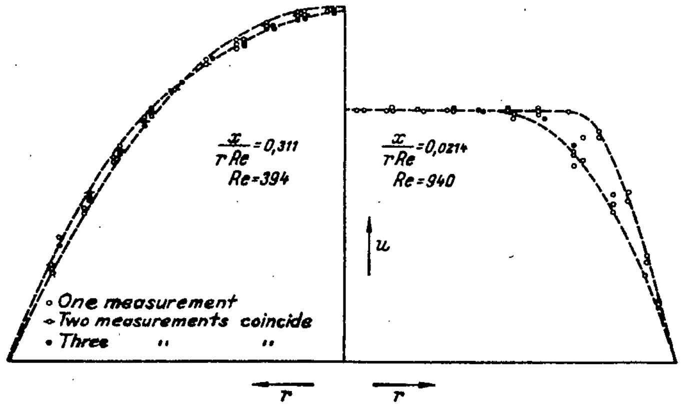


Figure 10.- Scatter of the velocity profile in the inlet section.

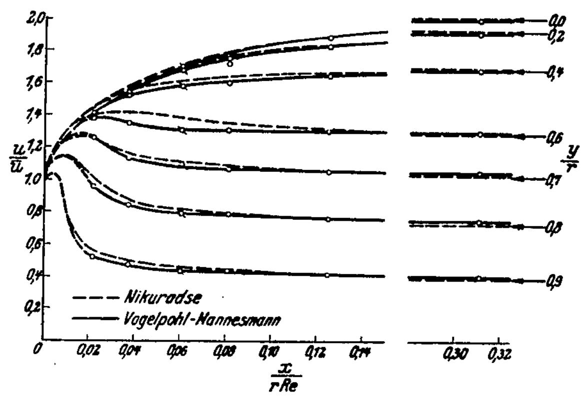


Figure 11.- Velocity profile in inlet region. Arrows denote Poiseuille parabola.

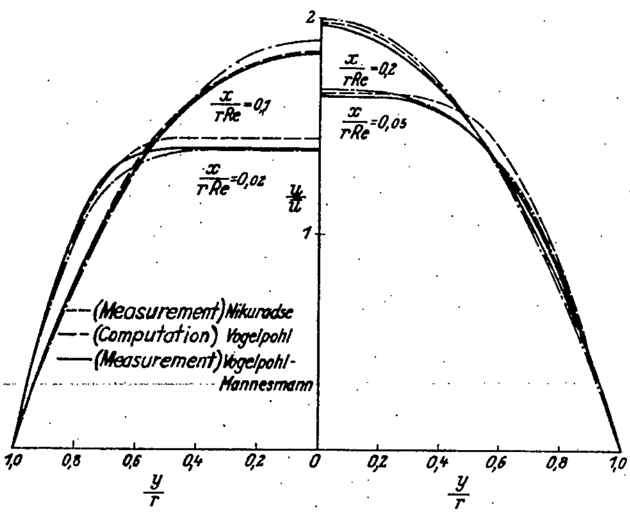


Figure 12.- Comparison with other investigation results.